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(54) **THREE-DIMENSIONAL HIGH VOLTAGE GATE DRIVER INTEGRATED CIRCUIT**

(52) **U.S. Cl.**
CPC **H01L 21/8234** (2013.01); **H01L 29/66681** (2013.01)

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USPC **438/109**; 327/108; 257/E21.705

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(58) **Field of Classification Search**
None
See application file for complete search history.

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(56) **References Cited**

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Related U.S. Application Data

(63) Continuation of application No. 13/588,429, filed on Aug. 17, 2012, now Pat. No. 8,791,723.

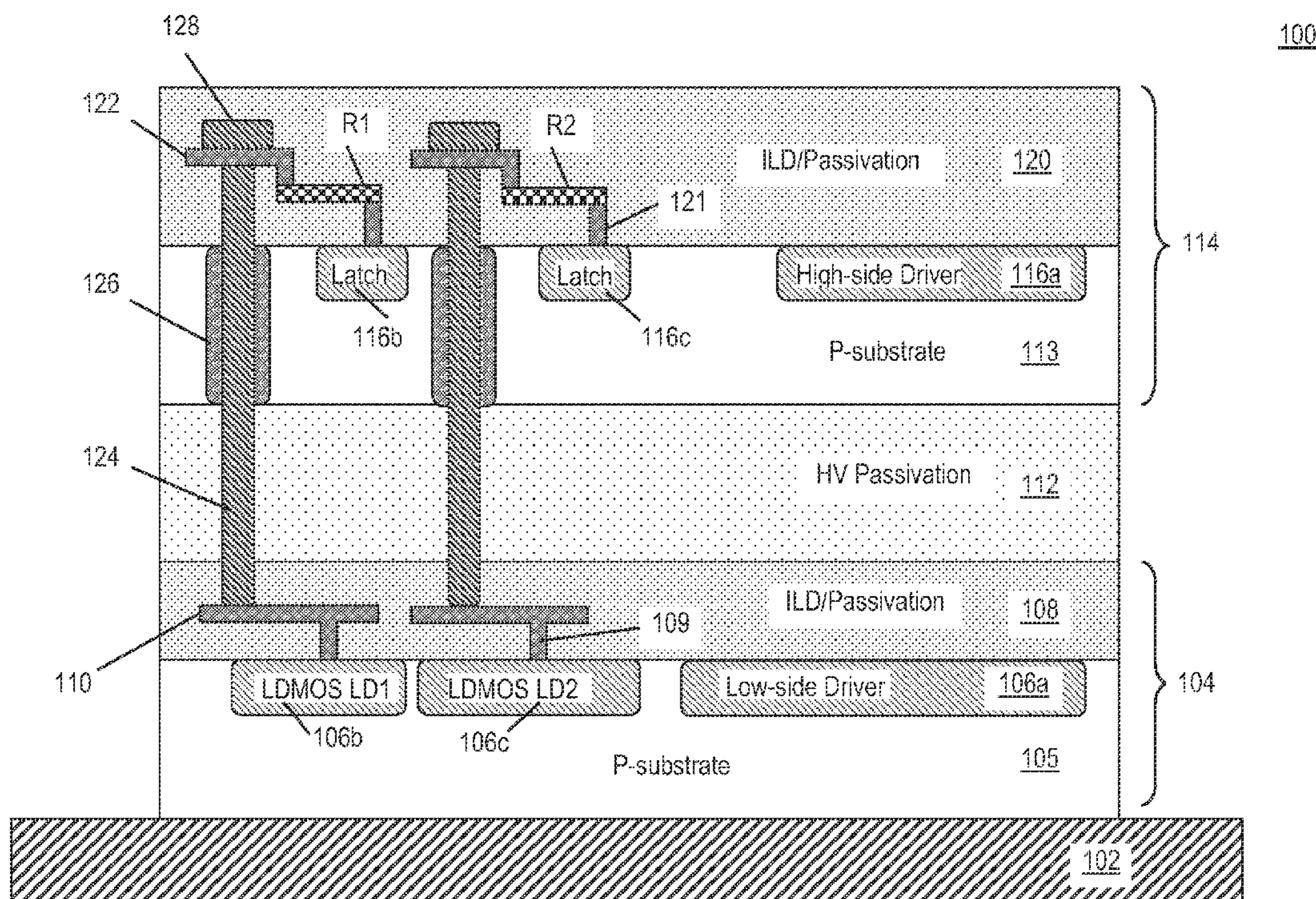
(57) **ABSTRACT**

A three-dimensional (3D) gate driver integrated circuit includes a high-side integrated circuit stacked on a low-side integrated circuit where the high-side integrated circuit and the low-side integrated circuit are interconnected using through-silicon vias (TSV). As thus formed, the high-side integrated circuit and the low-side integrated circuit can be formed without termination regions and without buried layers. The 3D gate driver integrated circuit improves ease of high voltage integration and improves the ruggedness and reliability of the gate driver integrated circuit.

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H03K 3/353 (2006.01)
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H01L 29/66 (2006.01)

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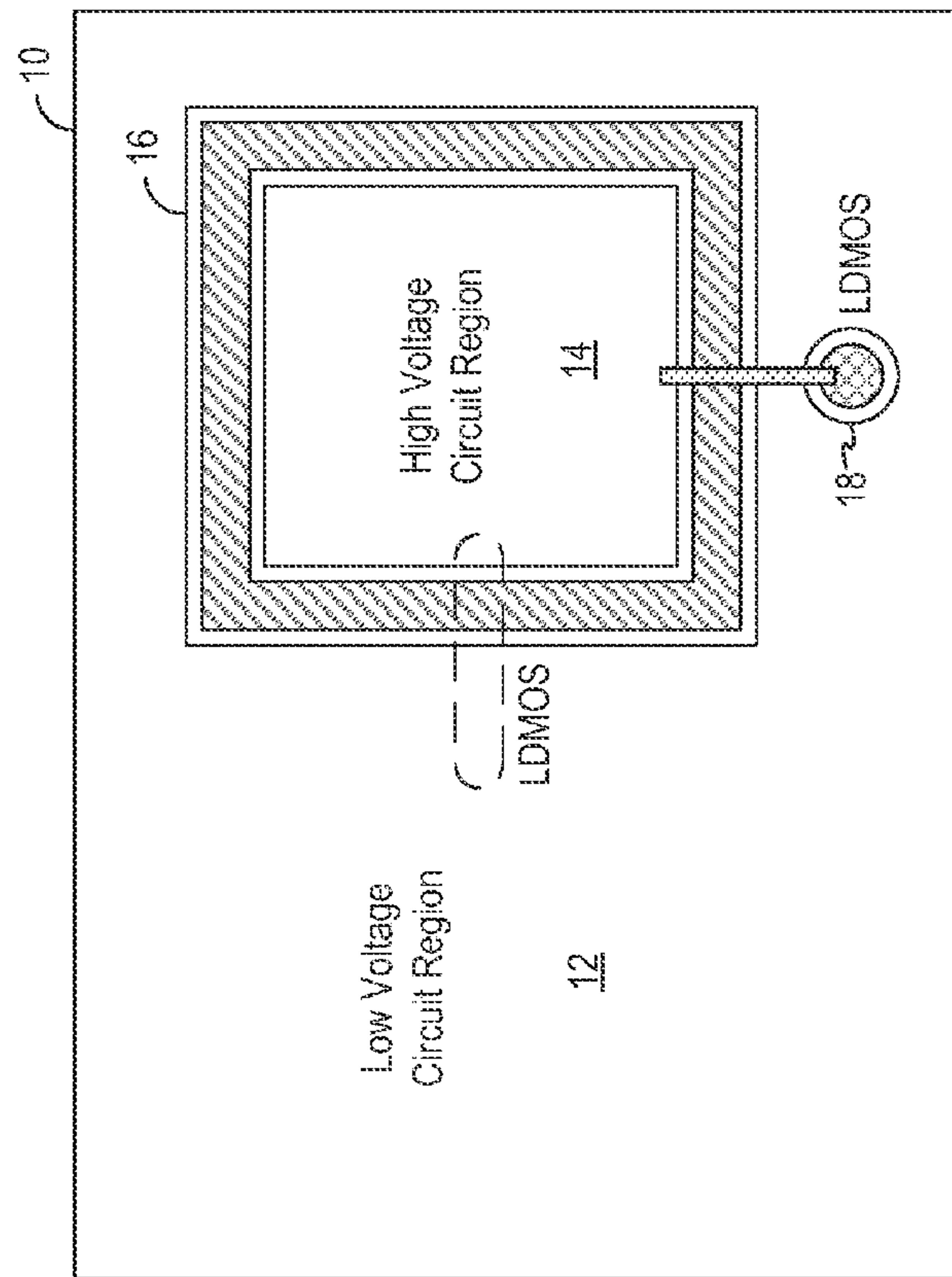


Fig. 1
(Prior Art)

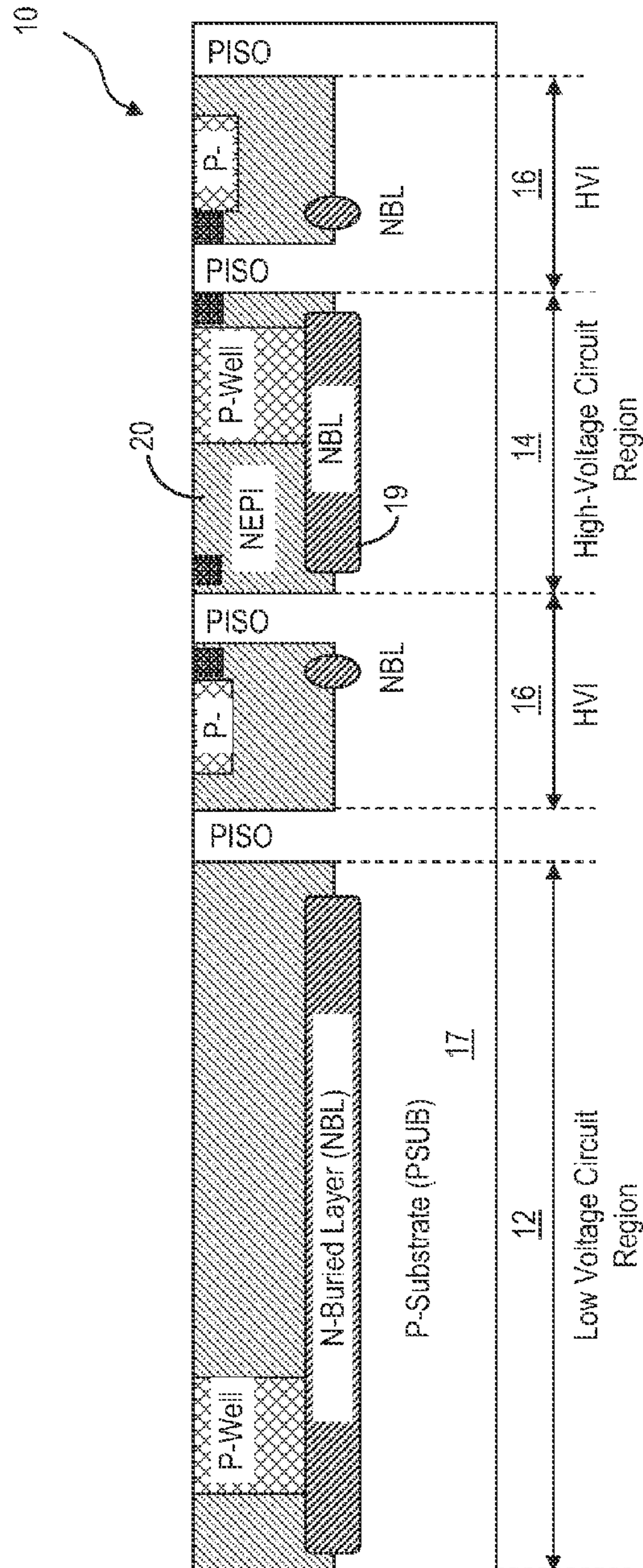


Fig. 2
(Prior Art)

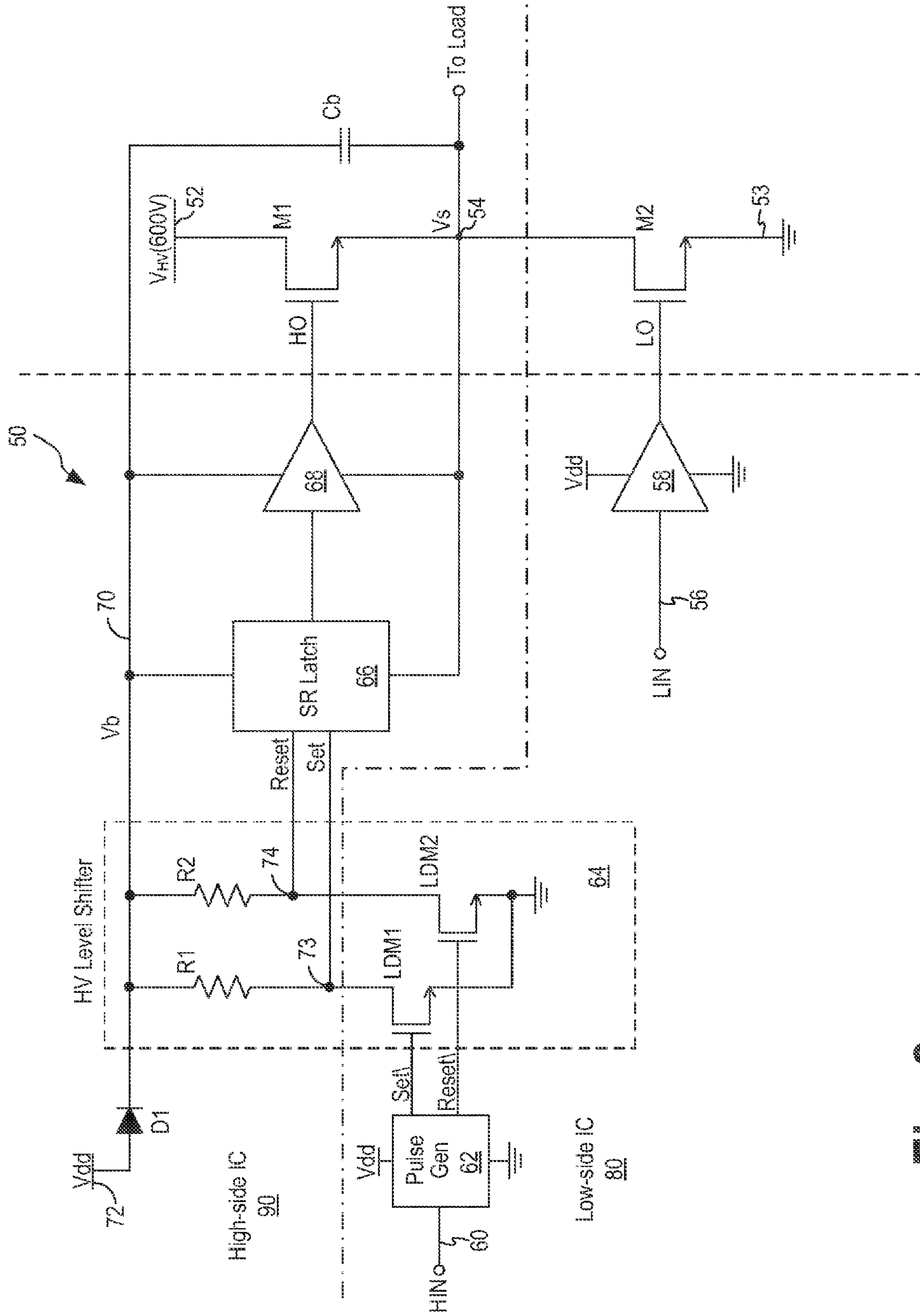


Fig. 3

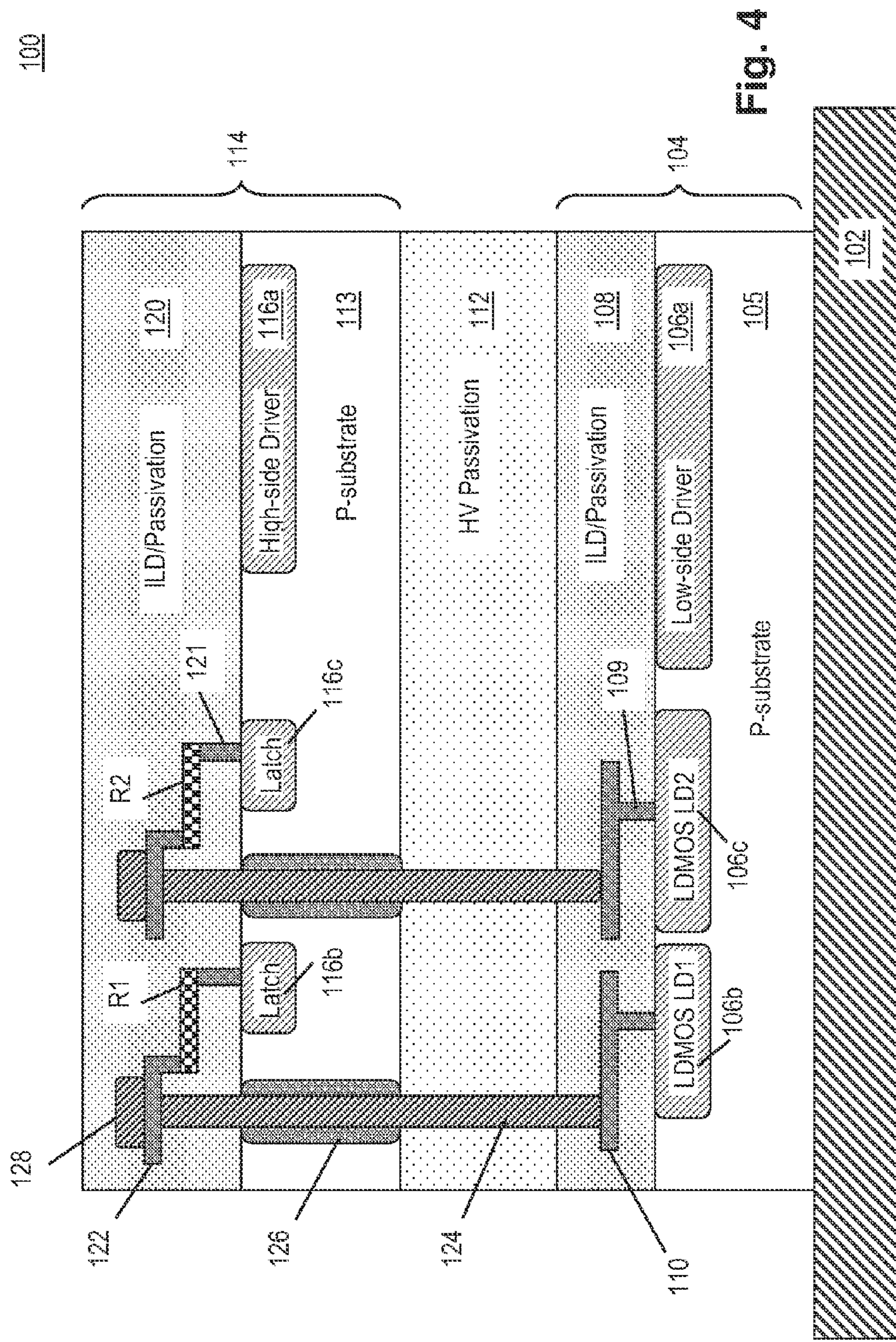


Fig. 4

200

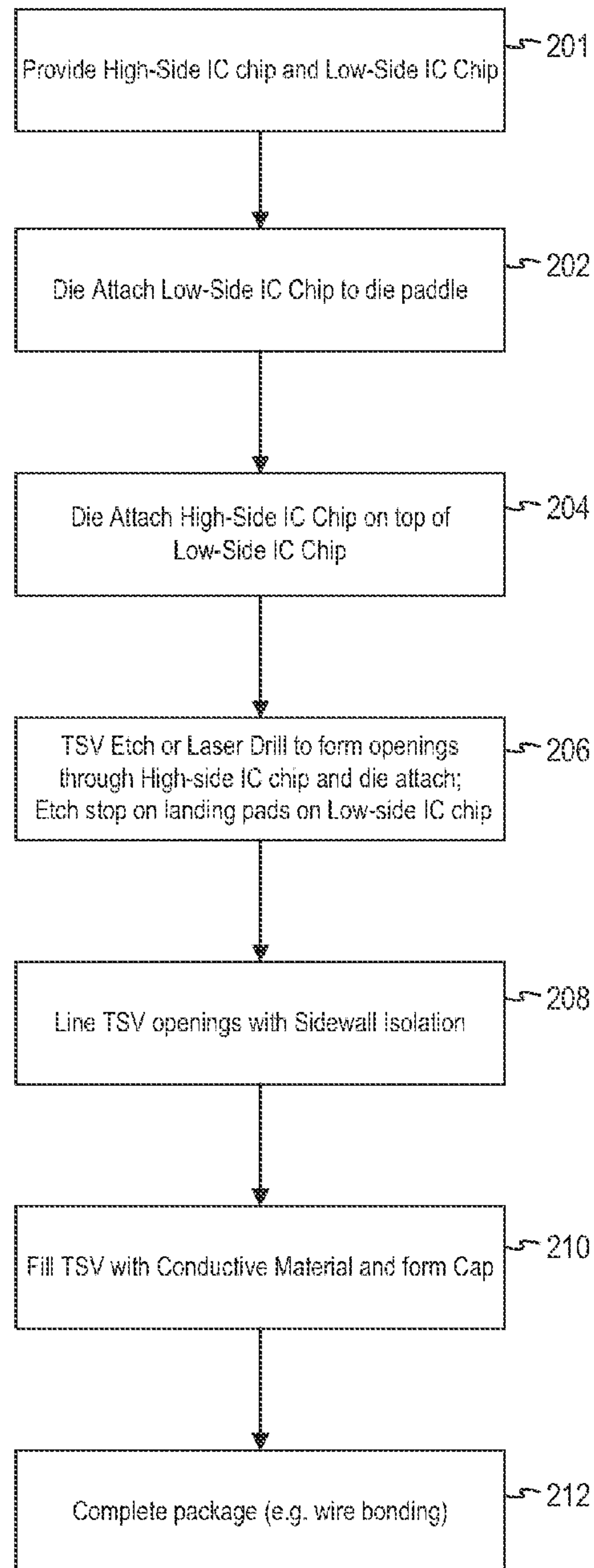


Fig. 5

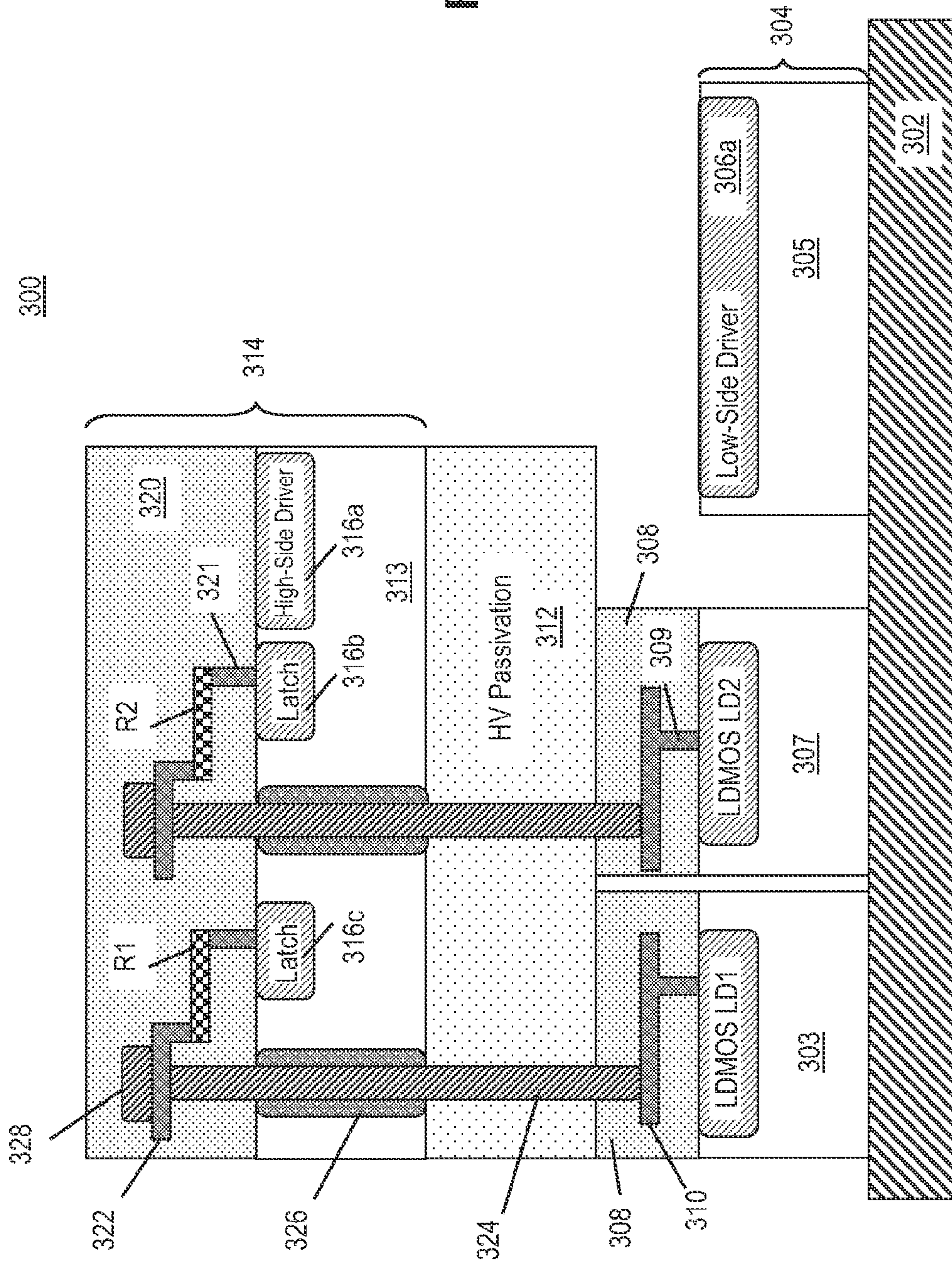


Fig. 6

400

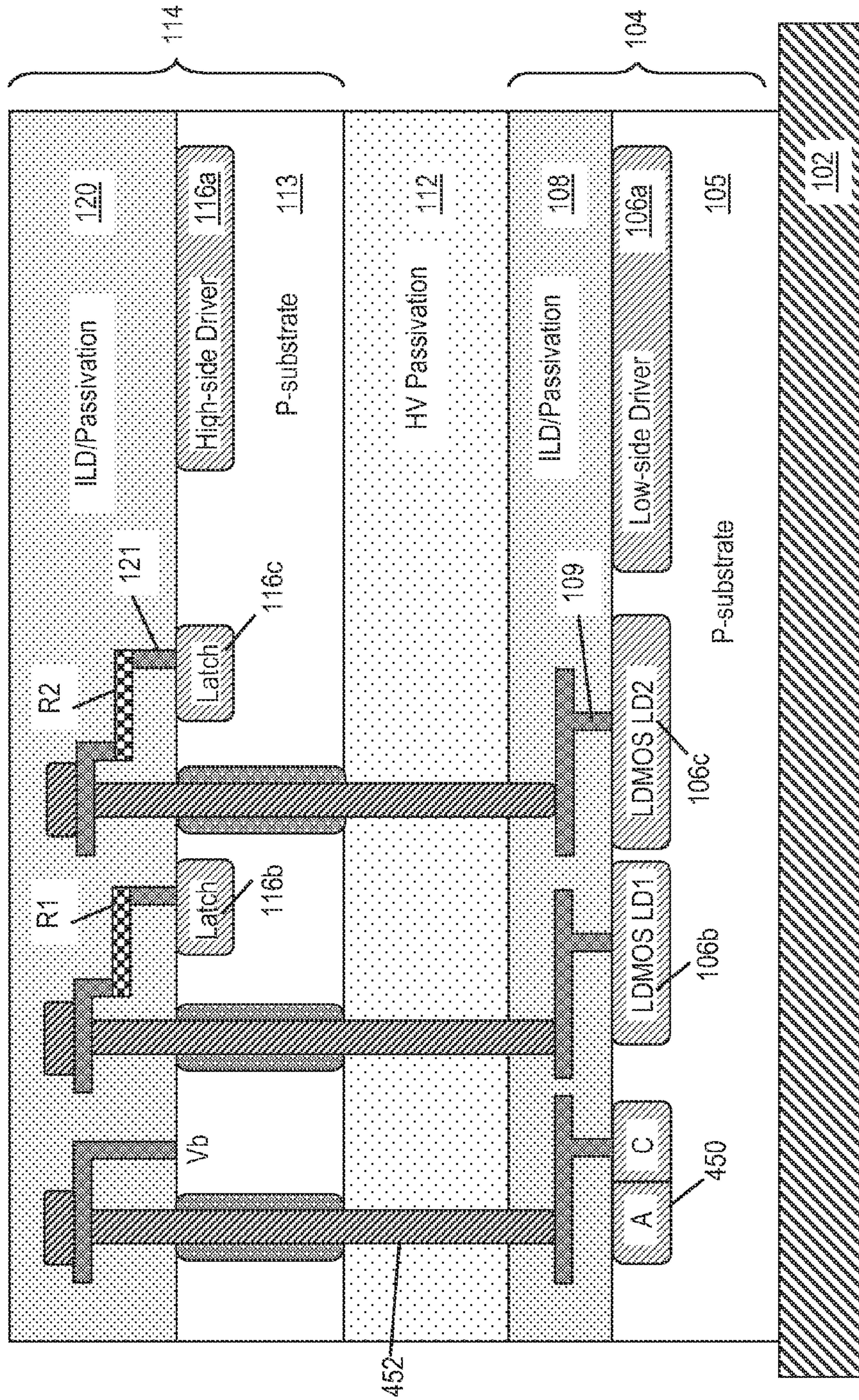


Fig. 7

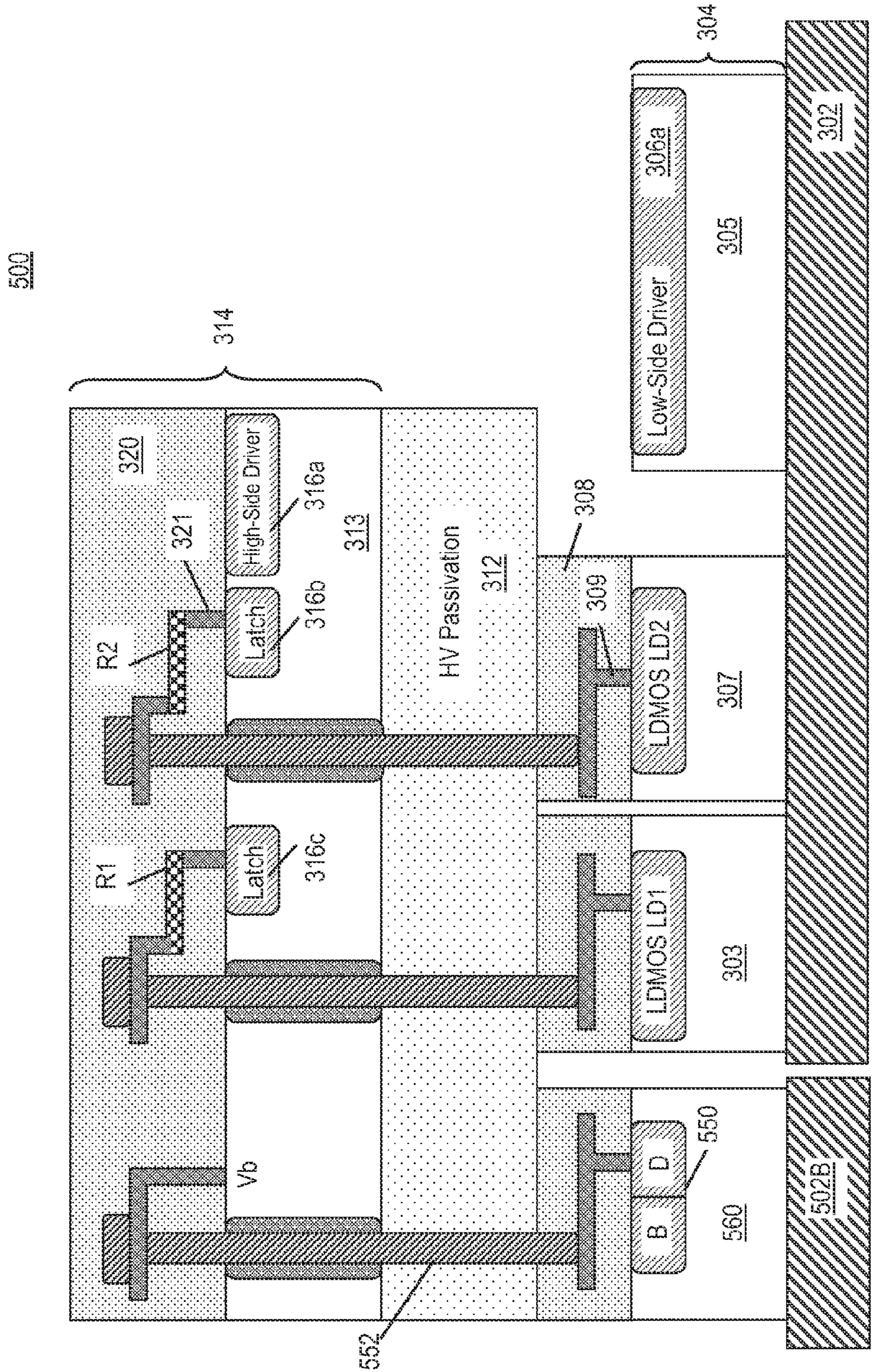


Fig. 8

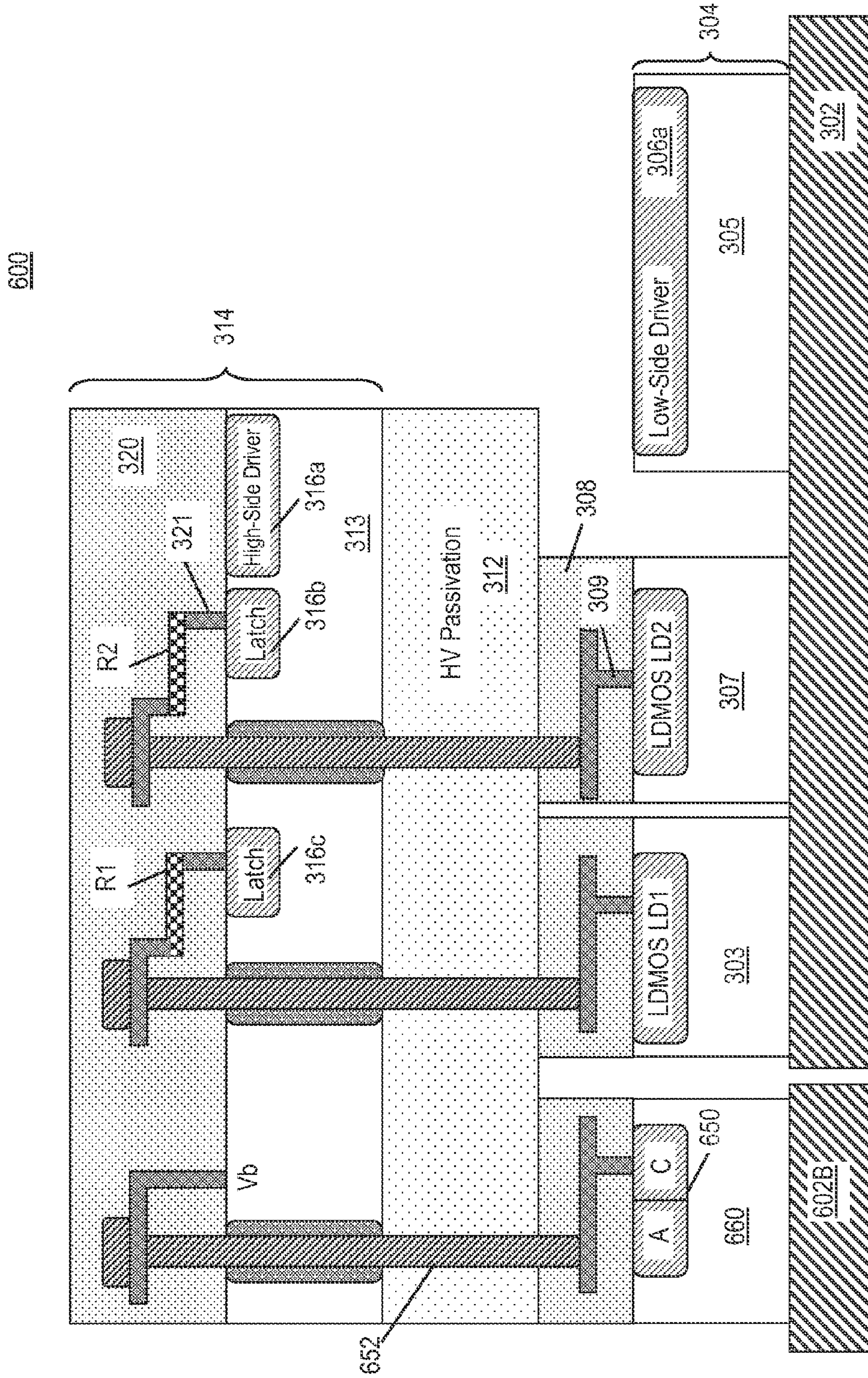


Fig. 9

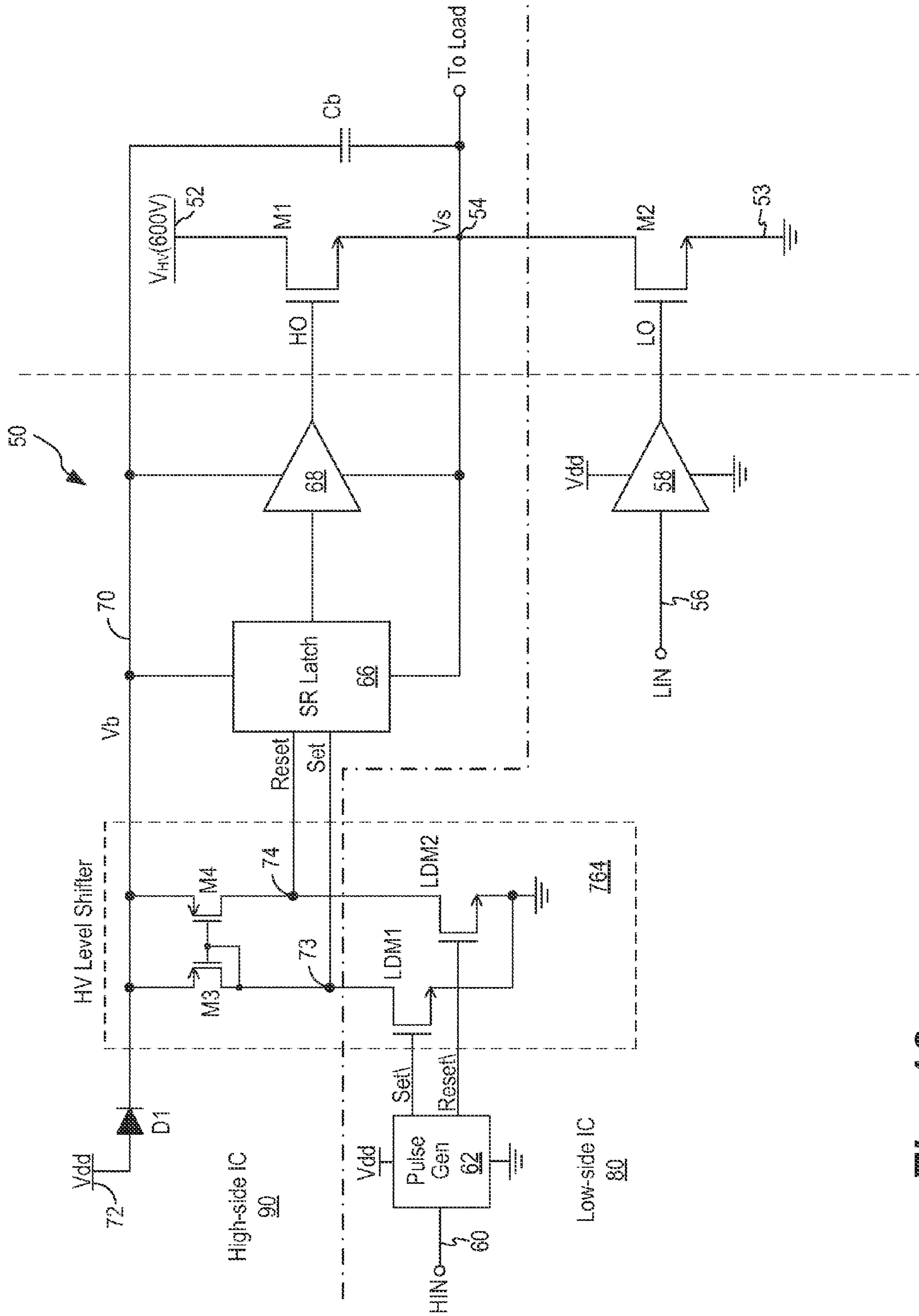


Fig. 10

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THREE-DIMENSIONAL HIGH VOLTAGE GATE DRIVER INTEGRATED CIRCUIT

CROSS REFERENCE TO OTHER APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 13/588,429, now U.S. Pat. No. 8,791,723, issued on Jul. 29, 2014, entitled THREE-DIMENSIONAL HIGH VOLTAGE GATE DRIVER INTEGRATED CIRCUIT filed Aug. 17, 2012, which is incorporated herein by reference for all purposes.

FIELD OF THE INVENTION

The invention relates to high voltage gate driver integrated circuits and, in particular, to a high voltage gate driver integrated circuit that is three-dimensional.

DESCRIPTION OF THE RELATED ART

Gate driver circuits, including high-side and low-side drivers, are used to drive power MOSFET or IGBT output transistors which are often applied in high voltage applications, such as motors. In some applications, the high-side driver is used to drive an N-channel power MOSFET in the high-side configuration which operates up to 600V. Conventional high voltage gate driver circuits integrate both the high-side gate driver and the low-side gate driver onto the same integrated circuit. FIG. 1 is a top view of a conventional high voltage gate driver integrated circuit and FIG. 2 is a cross-sectional view of the conventional high voltage gate driver integrated circuit of FIG. 1. Referring to FIGS. 1 and 2, a high voltage gate driver integrated circuit 10 typically includes a low voltage circuit region 12 and a high voltage circuit region 14 inside a high voltage floating tub. In the present description, the term "high voltage circuit region" refers to a circuit region of low voltage circuits that are sitting inside a high voltage floating tub. A junction termination region 16 is disposed between the low voltage region 12 and the high voltage floating tub. One or more N-type lateral double-diffused MOS (LDMOS) transistors 18 are disposed in the low voltage region 12 for shifting a signal voltage referenced to ground to a signal voltage referenced to the high voltage floating tub.

The junction termination region 16 provides an electrical isolation between the low voltage circuit region 12 and the high voltage circuit region 14. In some applications, the junction termination region 16 may include isolation structures and a reduced surface field (RESURF) structure. The junction termination region 16 must have enough width to ensure high reliability of the high voltage gate driver integrated circuit 10. In particular, the junction termination region 16 must have a relatively large width in order to ensure a breakdown voltage of about 600V or more and prevent malfunction of the high voltage gate driver integrated circuit 10 due to punch-through effect resulting from the formation of a depletion region. Therefore, the conventional high voltage gate driver integrated circuit 10 is relatively large in size. Some conventional high voltage gate driver circuits utilize a merged LDMOS transistor, as shown by the dotted line in FIG. 1, to reduce the size of the integrated circuit. However, the size of the junction termination region 16 is not reduced and the integrated circuit size remains large.

The high voltage gate driver integrated circuit 10 also employs N-type buried layer structure 19 formed between the P-type substrate 17 and the N-type epitaxial layer 20. The N-type buried layer 19 (NBL) is formed in both the high

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voltage circuit region 14 and the low voltage circuit region 12 to provide a low resistance path for parasitic substrate conduction to prevent latch-up. Buried layers require additional processing steps in the fabrication of the high voltage gate driver integrated circuit and thus increase the cost of manufacturing.

SUMMARY OF THE INVENTION

According to one embodiment of the present invention, a three-dimensional gate driver integrated circuit includes a low-side integrated circuit having formed thereon a low-side driver and a first LDMOS transistor where the low-side integrated circuit receives a low-side input signal and a high-side input signal and provides a low-side output signal; a high-side integrated circuit having formed thereon a high-side driver, a first resistor, and a latch circuit, the high-side integrated circuit providing a high-side output signal; a high voltage passivation layer formed between the low-side integrated circuit and the high-side integrated circuit; a through-silicon via formed in the high-side integrated circuit and the high voltage passivation layer where the through-silicon via electrically connects the first resistor to a drain terminal of the first LDMOS transistor formed on the low-side integrated circuit. In operation, the first LDMOS transistor and the first resistor form a level shifter circuit. The first LDMOS transistor receives a first signal relating to the high-side input signal and provides a first level-shifted signal to the latch circuit. The latch circuit generates a drive signal for driving the high-side driver.

According to another aspect of the present invention, a method for forming a three-dimensional gate driver integrated circuit includes providing a low-side integrated circuit having formed thereon a low-side driver and a first LDMOS transistor where the low-side integrated circuit receives a low-side input signal and a high-side input signal and provides a low-side output signal; providing a high-side integrated circuit having formed thereon a high-side driver, a first resistor, and a latch circuit where the high-side integrated circuit provides a high-side output signal; attaching the low-side integrated circuit to a package die paddle; attaching the high-side integrated circuit to the low-side integrated circuit through a high voltage passivation layer; etching a through-silicon via opening in the high-side integrated circuit and the high voltage passivation layer where the through-silicon via opening contacts the first resistor and extends to a drain terminal of the first LDMOS transistor formed on the low-side integrated circuit; forming a conductive material in the through-silicon via opening where the through-silicon via thus formed electrically connects the first resistor to the drain terminal of the first LDMOS transistor. In operation, the first LDMOS transistor and the first resistor form a level shifter circuit. The first LDMOS transistor receives a first signal relating to the high-side input signal and provides a first level-shifted signal to the latch circuit. The latch circuit generates a drive signal for driving the high-side driver.

The present invention is better understood upon consideration of the detailed description below and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a top view of a conventional high voltage gate driver integrated circuit.

FIG. 2 is a cross-sectional view of the conventional high voltage gate driver integrated circuit of FIG. 1.

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FIG. 3 is a circuit diagram of a high voltage gate driver circuit according to one embodiment of the present invention.

FIG. 4 is a cross-sectional view of a 3D gate driver integrated circuit according to one embodiment of the present invention.

FIG. 5 is a flowchart illustrating the method for forming a 3D gate driver integrated circuit according to one embodiment of the present invention.

FIG. 6 is a cross-sectional view of a 3D gate driver integrated circuit according to an alternate embodiment of the present invention.

FIG. 7 is a cross-sectional view of a 3D gate driver integrated circuit according to a second alternate embodiment of the present invention.

FIG. 8 is a cross-sectional view of a 3D gate driver integrated circuit according to a third alternate embodiment of the present invention.

FIG. 9 is a cross-sectional view of a 3D gate driver integrated circuit according to a fourth alternate embodiment of the present invention.

FIG. 10 is a circuit diagram of a high voltage gate driver circuit according to an alternate embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In accordance with the principles of the present invention, a three-dimensional (3D) gate driver integrated circuit includes a high-side integrated circuit stacked on a low-side integrated circuit where the high-side integrated circuit and the low-side integrated circuit are interconnected using through-silicon vias (TSVs). As thus configured, the high-side integrated circuit and the low-side integrated circuit can be formed without termination regions and without buried layers. The 3D gate driver integrated circuit of the present invention improves ease of high voltage integration and improves the ruggedness and reliability of the gate driver integrated circuit.

In one embodiment, a 3D gate driver integrated circuit includes a low-side integrated circuit having the low-side driver and the level shifter LDMOS transistor formed thereon and a high-side integrated circuit having the high-side driver formed thereon. The substrate of the high-side integrated circuit is floating and no buried layer is needed as there is no need to provide isolation from the P-substrate of the low-side driver. The high-side driver formed on the high-side integrated circuit is interconnected to the level shifter LDMOS using TSVs. In one embodiment, wire bonds connect the low-side driver on the low-side integrated circuit and the high-side driver on the high-side integrated circuit to package leads of the 3D gate driver integrated circuit.

FIG. 3 is a circuit diagram of a high voltage gate driver circuit according to one embodiment of the present invention. Referring to FIG. 3, a high voltage gate driver circuit 50 is disposed to drive a pair of N-channel power MOSFETs M1 and M2 connected in series between a high supply voltage V_{HV} (node 52) and the ground potential (node 53). In the present illustration, the high supply voltage V_{HV} is 600V or above. The N-channel MOSFET M1 thus has to operate up to 600V. The pair of N-channel power MOSFETs M1 and M2, under the control of the high-side drive signal HO and the low-side drive signal LO, are alternately turned on and off to generate an output voltage signal Vs (node 54) to drive a load.

High voltage gate driver circuit 50 includes a high-side driver 68 for generating the high-side drive signal HO to drive power MOSFET M1 and a low-side driver 58 for generating

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the low-side drive signal LO to drive power MOSFET M2. The gate driver circuit 50 receives a logic supply voltage Vdd (node 72). The gate driver circuit 50 also receives a boost supply voltage Vb (node 70) generated from the logic supply voltage Vdd and a boost capacitor Cb. More specifically, the capacitor Cb is connected between the boost supply voltage node 70 and the output voltage Vs (node 54). A diode D1 is interposed between the logic supply voltage Vdd (node 72) and the top plate of the capacitor Cb (node 70). More specifically, the anode of diode D1 is connected to the logic supply voltage (node 72) and the cathode of diode D1 is connected to the top plate (node 70) of the capacitor Cb. Diode D1 functions to charge the boost capacitor Cb when MOSFET M2 is turned on and to provide reverse blocking when MOSFET M1 is turned on. That is, diode D1 allows current to flow from the logic supply voltage Vdd to charge up capacitor Cb in a forward bias direction when MOSFET M2 is turned on. However, diode D1 prevents current from flowing back to the logic supply voltage node from the capacitor Cb when MOSFET M1 is turned on.

In operation, when the low-side power MOSFET M2 is turned on and the output voltage signal Vs is driven to ground, capacitor Cb is charged up by the logic supply voltage Vdd and a capacitor voltage Vc develops across the capacitor Cb where the capacitor voltage Vc is approximately the logic supply voltage Vdd, such as around 25V when Vdd=25V. When the high-side power MOSFET M1 is turned on, the output voltage signal Vs is driven towards the high supply voltage V_{HV} and the boost supply voltage Vb is boosted to a voltage value of Vs+Vc, such as around 600V+25V=625V when V_{HV} =600V. The high-side drive signal HO is driven to the boosted voltage Vb (e.g. 625V) when the high-side power MOSFET M1 is to be turned on. The output voltage signal Vs can thus be driven to the full value of the high supply voltage V_{HV} (e.g. 600V).

The low-side driver 58 receives a low-side input signal LIN (node 56) which can be a CMOS or TTL compatible logic input signal. The input signal LIN is a pulse-width modulation (PWM) signal generated from a micro-controller. The low-side driver 58 converts the input signal LIN onto the low-side drive signal LO. The low-side driver 58 is powered by the logic supply voltage Vdd. On the other hand, the high-side driver 68 is driven by a high-side input signal HIN (node 60) which is also a PWM signal generated by a micro-controller. However, the high-side drive signal coupled to the high-side driver 68 is powered by the boost supply voltage Vb. More specifically, the high-side input signal HIN (node 60) is coupled to a pulse generator 62 which is powered by the logic supply voltage Vdd. The pulse generator 62 generates Set-bar (Set $\bar{\backslash}$) and Reset-bar (Reset $\bar{\backslash}$) signals for driving a high voltage level shifter circuit 64. The high voltage level shifter circuit 64 includes a pair of high voltage LDMOS transistors LDM1 and LDM2. LDMOS transistor LDM1 is controlled by the Set $\bar{\backslash}$ signal and is coupled through a resistor R1 to the boost supply voltage Vb (node 70). LDMOS transistor LDM2 is controlled by the Reset $\bar{\backslash}$ signal and is coupled through a resistor R2 to the boost supply voltage Vb (node 70). When one of LDMOS transistors LDM1 and LDM2 is turned on by the respective Set $\bar{\backslash}$ and Reset $\bar{\backslash}$ signals, the drain of the LDMOS transistor is pulled low and a voltage of Vb minus the voltage drop across the resistor R1 or R2 develops at the drain node 73 or 74.

Assuming resistors R1 and R2 have the same resistance value, the voltage at the drain nodes 73, 74 of the LDMOS transistors is given as $Vb - V_R$, where V_R denotes the voltage drop across the resistor R1 or R2. When the high-side driver 68 is activated to a logical high level at the boost voltage Vb,

the boost supply voltage V_b is elevated to V_s+V_c , such as 625V, and the drain nodes **73**, **74** of the LDMOS transistors are driven to about 600, assuming voltage V_R is about 25-30V. The high voltage LDMOS transistors **LDM1** and **LDM2** operate to level shift the Set and Reset signals generated by the pulse generator **62** to a voltage level needed for driving the high-side driver **68**. The level-shifted Set and Reset Signals (nodes **73**, **74**) are coupled to drive a SR latch **66** which is powered by the boost supply voltage V_b . SR latch **66** generates the pulse signal for driving high-side driver **68**.

In the present embodiment, the high voltage gate driver circuit **50** employs two level shifting LDMOS transistors to generate the level-shifted Set and Reset signals for driving the high-side driver **68**. In other embodiments, a single level-shifting LDMOS transistor can be used to convert the high-side input signal HIN to a drive signal for the high-side driver **68**. The use of two level-shifting LDMOS transistors provides advantages in matching the turning on and off of the low-side and high-side drive signals.

The high voltage gate driver circuit **50** may further include other circuitry such as UVLO (undervoltage-lockout) circuits associated with the high-side driver and low-side driver to detect an undervoltage condition and to shut down the gate driver circuit should the supply voltages fall below the operational range.

As thus configured, the high voltage gate driver circuit **50** includes circuit elements that are operated at a high voltage, such as a voltage value close to the high supply voltage V_{HV} , and circuit elements that are operated at the logic supply voltage V_{dd} . The high voltage gate driver circuit **50** thus includes a high voltage circuit region above the dot-dash line where a high voltage floating tub is used to house the low voltage circuits including resistors **R1**, **R2**, the SR latch **66** and the high-side driver **68**. In the present description, the term "high voltage circuit region" refers to a circuit region of low voltage circuits that are sitting inside a high voltage floating tub.

The high voltage gate driver circuit **50** further includes a low voltage circuit region below the dot-dash line for housing the pulse generator **62**, the LDMOS transistors **LDM1** and **LDM2** and the low-side driver **58**. In conventional implementations such as that shown in FIGS. **1** and **2**, the high voltage floating tub is formed beside the low voltage circuit region with a large junction termination region surrounding the high voltage floating tub. Also, when the substrate is a P-type substrate, the high voltage floating tub may be formed in an N-type epitaxial layer or a P-type epitaxial layer formed over an N-type buried layer. When a P-type epitaxial layer is used, an N-type isolation structure around the N-buried layer is used to isolate the high voltage floating tub from the P-substrate. The junction termination region increases the size of the gate driver circuit when formed as a monolithic integrated circuit and the buried layer increases manufacturing cost.

According to embodiments of the present invention, the high voltage gate driver circuit **50** is formed using a high-side integrated circuit **90** (above the dot-dash line) and a low-side integrated circuit **80** (below the dot-dash line). Thus, the resistors **R1**, **R2**, the SR latch **66**, and the high-side driver **68** are formed on the high-side IC **90** while the pulse generator **62**, the LDMOS transistors **LDM1** and **LDM2** and the low-side driver **58** are formed on the low-side IC **80**. The high-side integrated circuit is stacked on the low-side integrated circuit to form a three-dimensional gate driver integrated circuit. By forming the high voltage circuit region and the low voltage circuit region into separate integrated circuits, junction termination or isolation structures are eliminated. Furthermore, although the high voltage circuit region is formed in a high

voltage floating tub connected to the boost supply voltage V_b , such as the 625V boost supply voltage V_b , the high voltage circuit region houses low voltage circuits that have a limited operating voltage, such as a 25-30V circuit, where the operating voltage is determined by the boost supply voltage V_b to V_s voltage which is also the voltage V_c across the boost capacitor C_b . Therefore, the drain of the LDMOS transistors (nodes **73** and **74**) and the high-side driver **68** has an operating voltage range about the voltage V_c of the boost capacitor C_b even while all the circuit nodes are sitting on the boost supply voltage V_b . Thus, the isolation for the LDMOS transistor drain regions that are electrically connected to the high voltage integrated circuit **90** becomes simpler as the drain isolation only needs to withstand the voltage difference of V_c .

FIG. **4** is a cross-sectional view of a 3D gate driver integrated circuit according to one embodiment of the present invention. Referring to FIG. **4**, a 3D gate driver integrated circuit **100** includes a low-side integrated circuit **104** attached to a package die paddle **102**. The low-side integrated circuit **104** is formed on a P-type substrate **105** and includes N-tubs **106a** to **106c** in which low voltage circuitry associated with the low-side integrated circuit are formed. In particular, the low-side driver may be formed in an N-tub **106a**. Other control circuitry, including the UVLO circuits, may also be formed in the N-tub **106a**. The level shifting LDMOS transistors **LD1** is formed in an N-tub **106b** and the level shifting LDMOS transistor **LD2** is formed in an N-tub **106c**. The low-side integrated circuit **104** does not include any high voltage circuit elements except for the drain nodes of the level-shifting LDMOS transistors, the amount of isolation structures that are needed is minimized. Furthermore, N-tubs **106a-c** can be formed without the use of buried layers. In some cases, the low-side integrated circuit **104** can also be formed without the use of an N-type epitaxial layer.

The low-side integrated circuit **104** includes conductive landing pads **110** for connecting the drain terminal of the LDMOS transistors to the high-side integrated circuit **114**. The landing pads **110** are formed on an inter-layer dielectric layer **108** and connected to the drain terminal of the respective LDMOS transistors **LD1** and **LD2** through vias **109**. The low-side integrated circuit **104** is then passivated by a passivation layer **108**. In the present illustration, the inter-layer dielectric layer and the passivation layer are shown collectively as layer **108**. It is understood that layer **108** includes different insulating dielectric and passivation layers.

The high-side integrated circuit **114** is formed on a P-type substrate **113** and includes N-tubs **116a** to **116c** in which low voltage circuitry of the high-side integrated circuit are formed. The P-type substrate **113** is connected to the output voltage V_s node so that the substrate voltage switches between ground and the high supply voltage V_{HV} . In the present description, the P-type substrate **113** is sometimes referred to as being "floating" which refers to the fact that the substrate **113** is not connected to a fixed voltage potential but to a voltage value that varies between ground and the high supply voltage V_{HV} .

In particular, the high-side driver may be formed in an N-tub **116a**. Other control circuitry, including the UVLO circuits, may also be formed in the N-tub **116a**. The SR latch circuit is formed in N-tub **116b** and **116c**. Because the high-side integrated circuit **114** is formed as a standalone integrated circuit, the high-side integrated circuit **114** does not need any high voltage isolation (such as 625V isolation) since the high-side P-substrate **113** is connected to the output voltage V_s which serves as the ground reference for the high-side circuits. Furthermore, because the P-substrate **113** is "floating" and because the high-side integrated circuit **114** experi-

ences only a small voltage swing (30V) even though the circuitry are sitting on the high supply voltage ($\approx 600V$), N-tubs **116a-c** can be formed without the use of buried layers. In some cases, the high-side integrated circuit **114** can also be formed without the use of an N-type epitaxial layer.

Resistors **R1** and **R2** for the level shifter circuit are formed in the high-side integrated circuit **114** and insulated from the P-substrate **113** by an inter-layer dielectric layer **120**. The resistors **R1** and **R2** are connected to the SR latch circuit through vias **121**. The high-side integrated circuit **114** is then passivated by a passivation layer **120**. In the present illustration, the inter-layer dielectric layer and the passivation layer are shown collectively as layer **120**. It is understood that layer **120** includes different insulating dielectric and passivation layers.

In the present embodiment, the high-side integrated circuit **114** receives two input signals from the low-side integrated circuit **104**. More specifically, the drains of the level shifting LDMOS transistors are to be connected to respective resistors **R1** and **R2**. In embodiments of the present invention, the low-side integrated circuit **104** is coated with a high voltage passivation layer **112** and the high-side integrated circuit **114** is die-attached to the high voltage passivation layer **112**. Then the through-silicon via (TSV) structure is used to form the electrical connection between the LDMOS transistors and the resistors. In the present embodiment, two TSV structures **124** are formed to connect metal pads **122** connecting to resistors **R1** and **R2** to the landing pads **110** connecting to the drain of the LDMOS transistors. The TSV structures **124** include a TSV dielectric layer **126** formed along the sidewall of the via opening in the P-substrate **113**. In this manner, the TSV dielectric layer **126** provides isolation of the conductive material in the TSV from the P-type substrate **113**. The TSV dielectric layer **126** only needs to be a low voltage isolation material, such as 30V-50V. This is because there is only a small voltage difference (e.g., 30V) between the voltage of the TSV node and the P-type substrate **113**, even though both are sitting on the high supply voltage value (600V). The TSV structures **124** may be covered by a cap layer **128**.

As thus formed, a 3D gate driver integrated circuit is formed where the high voltage circuit region and the low voltage circuit region are formed in separate integrated circuits and are stacked and interconnected through TSVs. Connections of the 3D gate driver integrated circuit to external package leads can be accomplished through wire bonding to the high-side integrated circuit and the low-side integrated circuit (not shown). The external connections can include the high-side and low-side input logic signals **HIN**, **LIN**, the logic supply voltage **Vdd**, the boost supply voltage **Vb**, and the high-side and low-side output signals **HO** and **LO**.

In the embodiment shown in FIG. 4, two level-shifting LDMOS transistors are used to level-shift the Set and Reset signals through resistors **R1** and **R2** to the high-side driver. In other embodiments, the high voltage gate driver circuit may be implemented using only one level-shifting LDMOS transistor and one corresponding resistor. The use of two level-shifting LDMOS transistors in FIG. 4 is illustrative only.

The advantages of the 3D gate driver integrated circuit of the present invention are numerous. First, the 3D gate driver integrated circuit is scalable and can operate at a high supply voltage of 600-1200V. Second, the 3D stacking architecture reduces chip footprint versus one-dimensional planar gate driver IC architecture. Third, by separating the high-side and low-side circuit regions into separate integrated circuits, there is no need for a high voltage termination area, buried layer, or epitaxial layers. The size of the integrated circuit can be reduced as well as reducing the manufacturing cost. Fourth,

because the N-buried layer is removed, delays in the driver circuit are reduced as the N-tub capacitance is reduced. Fifth, by separating the high voltage circuit region and the low voltage circuit region into separate integrated circuit chips, the ruggedness of the gate driver circuit is improved as the gate driver is immune to latch-up. Finally, it is easier to pass reliability tests such as HTRB (High Temperature Reverse Bias) since the high-side driver N-tubs are physically separated from low-side driver N-tubs.

FIG. 5 is a flowchart illustrating the method for forming a 3D gate driver integrated circuit according to one embodiment of the present invention. Referring to FIG. 5, a method **200** for forming a 3D gate driver integrated circuit starts by providing a high-side integrated circuit (IC) chip and a low-side integrated circuit (IC) chip (step **201**). The low-side IC chip includes the low voltage circuits such as the low-side driver, control circuitry and the level shifting LDMOS transistors. The high-side IC chip includes the high voltage circuits such as the high-side driver, the RS latch circuit and the resistors for the level shifter circuit. The method **200** proceeds by attaching the low-side IC chip to a package die paddle, such as using a die attach (step **202**). Then the high-side IC chip is attached to the top of the low-side IC chip, such as using a die attach (step **204**).

In some embodiments, the low-side IC chip has formed thereon a high voltage passivation layer and the high-side IC chip is attached to the top of the high voltage passivation layer. In other embodiments, a high voltage passivation layer can be formed on the backside of the high-side integrated circuit and then the high-side integrated circuit with the high voltage passivation layer is attached to the low-side integrated circuit and/or discrete LDMOS transistors.

Then, a through-silicon via (TSV) etch or laser drill process is performed to form openings through the high-side IC chip, the die attach, and the passivation layer on the low-side IC chip (step **206**). The landing pads on the low-side IC chip serve as the etch stop for the TSV etch. The TSV openings are then lined with sidewall isolation (step **208**). The sidewall isolation only needs to be of a low voltage rating, such as 30-50V, as the voltage difference between the TSV node and the high-side IC chip substrate is only 30-50V.

The TSV openings are then filled with a conductive material and each filled via is sealed by a cap (step **210**). Then, wire bonding is performed to form the connections of the 3D gate driver integrated circuit to external package leads (step **212**).

In the embodiments described above, the low-side integrated circuit in the 3D gate driver integrated circuit is formed as a monolithic integrated circuit including the low-side driver circuitry and the LDMOS transistors. In other embodiments, the low-side integrated circuit can be formed as separate integrated circuit chips using discrete LDMOS transistors. FIG. 6 is a cross-sectional view of a 3D gate driver integrated circuit according to an alternate embodiment of the present invention. Referring to FIG. 6, the 3D gate driver integrated circuit **300** includes a low-side integrated circuit **304** having formed thereon the low-side driver and other control circuitry, such as the UVLO circuit. The low-side integrated circuit **304** may be formed on a P-type substrate **305** with an N-tub **306a** for the low voltage circuits. The low-side integrated circuit **304** is die attached to a die paddle **302**.

The 3D gate driver integrated circuit **300** further includes a pair of bottom-source discrete LDMOS transistor devices **303** and **307**. Discrete LDMOS transistors are commercially available. In some embodiments, a single integrated circuit may include dual discrete bottom-source LDMOS transistors. Alternately, a pair of bottom-source discrete trench

DMOS transistor devices can be used. In embodiments of the present invention, landing pads **310** are formed on an inter-layer dielectric layer **308** to make electrical contact with the drain terminals of the discrete LDMOS devices **303** and **307** through vias **309**. Each discrete LDMOS devices **303, 307** are then covered by a passivation layer **308**. In the present illustration, the inter-layer dielectric layer and the passivation layer are collectively referred to as layer **308**. A high voltage passivation layer **312** is then formed over the discrete LDMOS devices **303, 307**. The high-side integrated circuit **314** is then attached to the high voltage passivation layer **312**. Through-silicon via structures **324** are then formed to realize the electrical connection between the resistors **R1** and **R2** in the high-side integrated circuit **314** and the drain terminals of the discrete LDMOS transistors **303, 307**, in the same manner as described above with reference to FIG. 4.

In embodiments of the present invention, the 3D gate driver integrated circuit includes the boost diode **D1** (FIG. 3) integrated with the low-side integrated circuit. FIG. 7 is a cross-sectional view of a 3D gate driver integrated circuit according to a second alternate embodiment of the present invention. Referring to FIG. 7, in the present embodiment, a 3D gate driver integrated circuit **400** includes a boost diode **450** formed on the P-substrate **105** of the low-side integrated circuit **104**. The cathode terminal of the boost diode **450** is connected through a TSV **452** to the boost supply voltage **Vb** node on the high-side integrated circuit **114**. The anode terminal of the boost diode **450** may be connected through a bond wire or a metal bus to the logic supply voltage **Vdd** node.

FIG. 8 is a cross-sectional view of a 3D gate driver integrated circuit according to a third alternate embodiment of the present invention. Referring to FIG. 8, in the present embodiment, a 3D gate driver integrated circuit **500** includes a boost diode **550** formed as a discrete N-type LDMOS transistor device **560**. More specifically, the gate and source terminals of the discrete LDMOS transistor device **560** are shorted together and also shorted to the P-type body. The N-type drain diffusion and the P-type body of the transistor form a body diode used as the boost diode **D1**. The cathode terminal (**D**) of the boost diode **550** is connected through a TSV **552** to the boost supply voltage **Vb** node on the high-side integrated circuit **314**. The anode terminal of the boost diode **550**, the body (**B**) of the LDMOS transistor, is connected through a die paddle portion **502b** which is connected to the logic supply voltage **Vdd** node. The die paddle portion **302** for the LDMOS transistor devices **303, 307** and the low-side driver **305** are connected to the ground potential.

In other embodiments, a discrete P-type LDMOS transistor device can be used as the boost diode **D1**. In that case, the N-type body, with the source and gate terminals shorted together, is the cathode of the diode and the P-type drain diffusion is the anode of the diode.

FIG. 9 is a cross-sectional view of a 3D gate driver integrated circuit according to a fourth alternate embodiment of the present invention. Referring to FIG. 9, in the present embodiment, a 3D gate driver integrated circuit **600** includes a boost diode **650** formed as a discrete Schottky diode device **660**. The cathode terminal of the boost diode **650** is connected through a TSV **652** to the boost supply voltage **Vb** node on the high-side integrated circuit **314**. The anode terminal of the boost diode **650** is connected through a die paddle portion **602b** which is connected to the logic supply voltage **Vdd** node. The die paddle portion **302** for the LDMOS transistor devices **303, 307** and the low-side driver **305** are connected to the ground potential.

In embodiments of the present invention, the boost diode can be formed using a discrete LDMOS transistor or a dis-

crete Schottky diode on an integrated circuit separate from the low-side integrated circuit including the low-side driver and the level-shifting LDMOS transistors. That is, referring to FIG. 7, instead of integrating the boost diode **450** onto the same substrate of the low-side integrated circuit **104**, the boost diode can be provided as discrete devices as shown in FIGS. 8 and 9.

In the above-described embodiments, the level shifter circuit is formed using resistors **R1** and **R2** as a passive load to the LDMOS transistors **LDM1** and **LDM2**. In other embodiments, the level shifter circuit may be implemented using other loading circuit, including passive load or active load, to transfer a signal from the low-side integrated circuit to a voltage value suitable for the high-side integrated circuit, that is a voltage between the boost supply voltage **Vb** and the output voltage **Vs**. In one embodiment, the level shifter circuit is implemented using a current mirror as an active load to the LDMOS transistors **LDM1** and **LDM2**. FIG. 10 is a circuit diagram of a high voltage gate driver circuit according to an alternate embodiment of the present invention. Like elements in FIGS. 3 and 10 are given like reference numerals to simplify the description. Referring to FIG. 10, the high voltage level shifter circuit **764** is formed using a current mirror circuit as an active load to the LDMOS transistors **LDM1** and **LDM2**. The current mirror circuit is formed by a diode-connected PMOS transistor **M3** acting as a current mirror and a PMOS transistor **M4** acting as a current source. The gate terminals of the PMOS transistors **M3** and **M4** are connected together. As thus configured, the current mirror circuit of PMOS transistors **M3** and **M4** provides active loading to the LDMOS transistors **LDM1** and **LDM2**. When implemented in the 3D gate driver integrated circuit, the PMOS transistors of the current mirror circuit is formed on the high-side integrated circuit and TSVs are formed to connect the drain nodes of the LDMOS transistor devices in the low-side integrated circuit to the drain terminals of the PMOS transistors **M3** and **M4** of the current mirror circuit.

In other embodiments, the level shifter circuit is implemented using a latch circuit as the active load and the drain terminals (nodes **73, 74**) of the LDMOS transistors are clamped to the output voltage **Vs** to prevent the drain nodes from dropping below voltage **Vs**. Other active or passive load circuits can be used to connect to the LDMOS transistors in the level shifter circuit. The use of resistors, PMOS current mirror, and latch circuit are exemplary only and not intended to be limiting.

The above detailed descriptions are provided to illustrate specific embodiments of the present invention and are not intended to be limiting. Numerous modifications and variations within the scope of the present invention are possible. The present invention is defined by the appended claims.

I claim:

1. A method for forming a three-dimensional gate driver integrated circuit, comprising:
 - providing a low-side integrated circuit having formed thereon a low-side driver and a first LDMOS (lateral double-diffused metal-oxide-semiconductor) transistor, the low-side integrated circuit receiving a low-side input signal and a high-side input signal and providing a low-side output signal;
 - providing a high-side integrated circuit having formed thereon a high-side driver, a first load circuit, and a latch circuit, the high-side integrated circuit providing a high-side output signal;
 - attaching the low-side integrated circuit to a package die paddle;

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attaching the high-side integrated circuit to the low-side integrated circuit through a high voltage passivation layer;

etching a through-silicon via opening in the high-side integrated circuit and the high voltage passivation layer, the through-silicon via opening contacting the first load circuit and extending to a drain terminal of the first LDMOS transistor formed on the low-side integrated circuit; and

forming a conductive material in the through-silicon via opening, the through-silicon via thus formed electrically connecting the first load circuit to the drain terminal of the first LDMOS transistor,

wherein the first LDMOS transistor and the first load circuit form a level shifter circuit, the first LDMOS transistor receiving a first signal relating to the high-side input signal and providing a first level-shifted signal to the latch circuit, the latch circuit generating a drive signal for driving the high-side driver.

2. The method of claim 1, further comprising:
before forming a conductive material in the through-silicon via opening, forming a sidewall dielectric layer at a portion of the via opening formed through the high-side integrated circuit.

3. The method of claim 2, wherein the sidewall dielectric layer is a low voltage dielectric layer.

4. The method of claim 1, wherein the low-side integrated circuit further comprises a landing pad electrically connected to the drain terminal of the first LDMOS transistor and etching a through-silicon via opening comprises etching the through-silicon via opening using the landing pad as an etch stop.

5. The method of claim 1, further comprising:
forming electrical connections to the low-side integrated circuit and the high-side integrated circuit for the low-side input signal, the high-side input signal, the low-side output signal and the high-side output signal.

6. The method of claim 5, wherein forming electrical connections to the low-side integrated circuit and the high-side integrated circuit comprises forming wire bonds to the low-side integrated circuit and the high-side integrated circuit.

7. The method of claim 1, further comprising:
forming a boost diode on the low-side integrated circuit; and

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connecting a cathode terminal of the boost diode by a third through-silicon via formed in the high-side integrated circuit and the high voltage passivation layer to a boost supply voltage node on the high-side integrated circuit.

8. The method of claim 1, further comprising:
providing a boost diode as a body diode of a discrete N-type LDMOS transistor device, the source, the gate, and the body terminals of the discrete LDMOS transistor device being electrically connected together, the discrete LDMOS transistor device being electrically connected to a first die paddle portion electrically isolated from a second die paddle portion on which the low-side integrated circuit is connected; and
connecting the drain terminal of the discrete LDMOS transistor device by a third through-silicon via formed in the high-side integrated circuit and the high voltage passivation layer to a boost supply voltage node on the high-side integrated circuit.

9. The method of claim 1, further comprising:
providing a boost diode formed as a discrete Schottky diode device, the discrete Schottky diode device being electrically connected to a first die paddle portion electrically isolated from a second die paddle portion on which the low-side integrated circuit is connected; and
connecting the cathode terminal of the discrete Schottky diode device by a third through-silicon via formed in the high-side integrated circuit and the high voltage passivation layer to a boost supply voltage node on the high-side integrated circuit.

10. The method of claim 1, wherein attaching the high-side integrated circuit to the low-side integrated circuit through a high voltage passivation layer comprises:
forming a high voltage passivation layer on a top side of the low-side integrated circuit; and
attaching the high-side integrated circuit to the high voltage passivation layer.

11. The method of claim 1, wherein attaching the high-side integrated circuit to the low-side integrated circuit through a high voltage passivation layer comprises:
forming a high voltage passivation layer on a backside of the high-side integrated circuit; and
attaching the high-side passivation layer to the low-side integrated circuit.

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